Using Wind Driven Tumbleweed Rovers to Explore Martian Gully Features

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Gully features have been observed on the slopes of numerous Martian crater walls, valleys, pits, and graben. Several mechanisms for gully formation have been proposed, including: liquid water aquifers (shallow and deep), melting ground ice, snow melt, CO_2 aquifers, and dry debris flow. Remote sensing observations indicate that the most likely *erosional agent* is liquid water. Debate concerns the source of this water. Observations favor a liquid water aquifer as the primary candidate. The current strategy in the search for life on Mars is to "follow the water." A new vehicle known as a Tumbleweed rover may be able to conduct in-situ investigations in the gullies, which are currently inaccessible by conventional rovers. Deriving mobility through use of the surface winds on Mars, Tumbleweed rovers would be lightweight and relatively inexpensive thus allowing multiple rovers to be deployed in a single mission to survey areas for future exploration. NASA Langley Research Center (LaRC) is developing deployable structure Tumbleweed concepts. An extremely lightweight measurement acquisition system and sensors are proposed for the Tumbleweed rover that greatly increases the number of measurements performed while having negligible mass increase. The key to this method is the use of magnetic field response sensors designed as passive inductor-capacitor circuits that produce magnetic field responses whose attributes correspond to values of physical properties for which the sensors measure. The sensors do not need a physical connection to a power source or to data acquisition equipment resulting in additional weight reduction. Many of the sensors and interrogating antennae can be directly placed on the Tumbleweed using film deposition methods such as photolithography thus providing further weight reduction. Concepts are presented herein for methods to measure subsurface water, subsurface metals, planetary winds and environmental gases.

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Nomenclature

A	=	amplitude
C	=	capacitor
$\frac{dA}{d\omega}$	=	change in amplitude with respect to change in frequency
δ	=	skin depth
H	=	magnetic field intensity
H_0	=	initial magnetic field intensity
L	=	inductor
t	=	time
ω	=	frequency of the field.
ω_1	=	baseline resonant frequency
ω_2	=	new resonant frequency
z	=	depth into the material

I. Introduction

Gully features on the slopes of numerous Martian crater walls, valleys, pits, and graben are of particular interest because of their apparent young age and the potential association with liquid water. Therefore, a primary scientific objective is to determine how the gullies formed, specifically, what is the agent of erosion and what is the source of the erosional agent? Several mechanisms for gully formation have been proposed including: liquid water aquifers (shallow[1] and deep[2]), melting ground ice,[3] snow melt,[4,5] CO_2 aquifers,[6] and dry debris flow.[7] Observational tests conducted using remote sensing by the Mars Global Surveyor Mars Orbiter Camera (MGS MOC), the Mars Orbiter Laser Altimeter (MOLA) and the Thermal Emission Spectrometer (TES) indicate that the most likely candidate of formation is liquid water,[8] and strongly favoring a liquid water aquifer as the source. Because the current strategy in the search for life on Mars is to "follow the water," these areas are of primary interest for conducting in situ investigations.

A vehicle with the ability to traverse across and around the gullies is needed to conduct in-situ measurements of the gully features. Current conventional designs of wheel driven rovers could not easily accomplish measurements across the gullies, however, a new unconventional rover known as a Tumbleweed rover could possibly be used.[9] Designed to derive mobility through use of the surface winds on Mars, Tumbleweed rovers would be lightweight and relatively inexpensive, allowing multiple rovers to be deployed in a single mission to particular areas of interest. The Tumbleweeds would complement currently planned missions by serving as scouts, pinpointing locations of interest for detailed follow-on investigations by rovers, landers, or perhaps human explorers. With Martian wind speeds typically 2-5 m/s during the day, with periodic gusts of 10-20 m/s and seasonal dust storms exceeding 25 m/s, all sensors and measurement acquisition equipment would need to be extremely lightweight to facilitate the Tumbleweed concept in the thin atmosphere of Mars. A recently developed measurement acquisition method has promise for providing the Tumbleweed rover with numerous sensors with a negligible aggregate mass.[10-12] Several efforts to develop Tumbleweed rovers are currently underway at the NASA Langley Research Center (LaRC),[13] the Jet Propulsion Laboratory (JPL),[14] Texas Technical University (TTU),[15] and North Carolina State University (NCSU).[16,17] The LaRC, NCSU and TTU efforts are studying deployable open-structure concepts while JPL is focusing on inflatable ball concepts.

II. Science Measurements

There are four areas of interest in and around the gullies: upslope plateau, alcove, channel, and debris apron (figure 1). The overlying flat plateau is typically broken by a crater, valley, pit, or graben, which creates a distinct break in slope or "ridge" above the gully alcove.[8] The alcoves emanate from a discrete distance below this overlying ridge.[8,18] The theater-shaped alcove generally tapers downslope and may represent a fluid source region.[8,18] The channels typically begin at the base of the alcove. Channels appear incised into the slope surface, having steep walls with a distinctive V-shaped cross section.[8,18] Near the alcove-channel transition there is sometimes evidence of channels streamlining around obstacles and anastomosing channel patterns.[8,18] The depositional aprons typically have a triangular shape which broadens downslope. The aprons appear smooth on a decameter scale but smaller swells and swales are observed that are oriented downslope along the long axis of the gully.[18] The following sections describe in-situ measurements that are desired in each of these locations to test the various proposed mechanisms of gully formation.

A. Upslope Plateau

Measurements of the upslope plateau would include elevation, subsurface sounding, and determination of overburden composition.

Elevation data across the upslope plateaus behind the gullies can be used to determine the horizontal extent of the plateau (currently with MOC narrow and wide angle images, the upslope plateau often extends beyond the images themselves). This data can then be used to calculate the hydraulic head to determine if the direction of the hydraulic gradient is consistent with the location of the gullies. For example, one might expect to find gullies on one side of the crater wall and not the other but only on the side where the downslope movement within the aquifer points towards the crater wall. If the direction of dip of the aquifer's confining strata layers is consistent with the location of the gullies along a crater wall then this observation would argue in favor of a shallow aquifer water source.

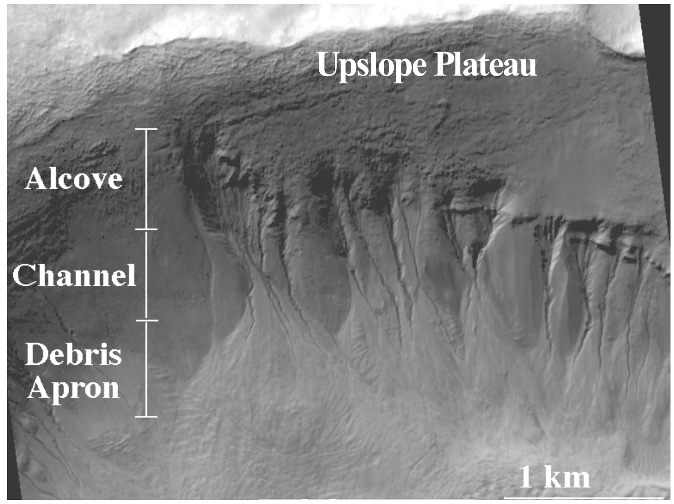


Figure 1. **Portion of MOC image M17-00423 located at 200.86°W, 39.16°S showing the alcove, channel, and debris apron structures of recent gullies on Mars. Scale bar is 1 km.**

Subsurface sounding of the upslope plateau is necessary to detect if a subsurface aquifer exists and to map out its planar extent. The size of the aquifer can place constraints on the amount of water available to form the gullies. Such information is valuable for understanding the nature and extent of the hydrologic cycle on Mars. This information will also be used to compare the amount of water potentially available in an aquifer (which is dependent upon the aquifer size) with combined modeling and geomorphology of predicted amounts of water that have run through the gullies to assess the consistency of such independent estimates of water volumes.

Determination of the overburden composition can be used for estimating the thermal conductivity of overburden since conductivities spanning from dry to ice-cemented soils can range over orders of magnitude. Thermal conductivity values are critical to subsurface temperature calculations, calculations of depth to 273K isotherm, and an analysis of effective conductivities required to see if the existence of a shallow aquifer is plausible.

B. Alcoves

Alcove investigations include testing the shallow aquifer theory by examining the proposed relationship between cohesive strata and gully alcoves, and examining several strata layers.

If there is an aquifer several 100 meters beneath the surface, an ice plug should exist at this depth beneath the overlying plateau but close to the cliff face surface. High-resolution data is needed to determine if there is ground ice associated with the locations of the alcoves along the cliff face. Imaging of the alcoves could yield insights into the nature of the underlying material (ice or rock?). Also, compositional data collected within the alcove regions could finally determine whether or not the enigmatic "pasted-on" deposits[4] filling some alcoves are composed of water ice/snow or some other material, which would help narrow down the possible gully formation mechanisms. The confirmation of solid water on the Martian surface would revolutionize our understanding of water on Mars.

MOC imagery suggests a genetic relationship between the alcove depths and the presence of cohesive strata layers in the subsurface. However, improved resolution is required to better understand this relationship. If water is trapped by these competent layers in an aquiclude, then the liquid may be seeping out around these outcrops. There may be some evidence of liquid on the exposed portions of the rock layers, requiring a test for chemical signatures (similar chemistries found here in the alcoves and within the debris aprons but not on the surrounding soils would be strong evidence for liquid water and would lend insights into the impurities in this water) and search for smaller scale morphologies indicative of fluvial erosion on these exposed surfaces.

Observation of several strata layers exposed at the cliff face facilitates in determining where the water is reaching the surface. The rover could also examine several strata layers exposed at the cliff face to pinpoint where the water is reaching the surface. Alcoves are usually embedded in morphologically indistinguishable layers (at MOC scales) and so the possibility exists that it can be determined which layers are trapping the H_2O.

C. Channel

Examination of the gully channel interiors would help in understanding the channel morphology and place constraints on flow rates, flow speeds, etc. Currently, the channels are at the limits of detection in MOC imagery and improved measurements are needed regarding channel bed shapes, channel depths, channel paths (i.e. deflection around obstacles), etc. to place constraints on the nature of the eroding fluid.

D. Debris Apron

Examination of soils in the debris aprons provides a means of ascertaining if the water emanating from the gully contains impurities, which should be deposited in the debris aprons and leave a chemical signature (e.g., salts or sulphates). Comparisons of the chemical signature of the debris aprons with surrounding terrain unaffected by gully flows provide a baseline to determine if the gully deposits are indeed unique to the gullies. Examining the debris aprons to determine the size distribution of particles being transported downslope has important implications for flow velocity which in turn is critical for determining flow timescales and the volume of water that could be transported through the gully systems.

III. NASA LaRC Tumbleweed Concepts

Tumbleweed rovers could be used to traverse across and around the gullies to conduct in-situ measurements. The NASA LaRC deployable structure concepts, depicted in figure 2,[13] are durable, provide superior aerodynamic properties, and allow open access to the environment for scientific instruments. The **"Box Kite"** concept employs fabric sails attached to spring hoops in the manner used in tents and automobile sunshades. Additional hoops (without sails) may be added to provide better rolling characteristics. The **"Dandelion"** concept uses a spherically symmetric array of struts, legs, spines, etc. The struts may have pads/feet at the ends to prevent sinking into soft soil, dust or sand. Another variation, the **"Eggbeater Dandelion."** uses multiple curved struts, resembling eggbeaters or whisks. The **"Tumble-cup"** consists of open-ended cylinders around a spherical core maximizing aerodynamic surface area to maximize the drag force while also reducing rolling resistance. Analysis and test of these concepts is being conducted at NASA LaRC to determine advantages and disadvantages of each design.

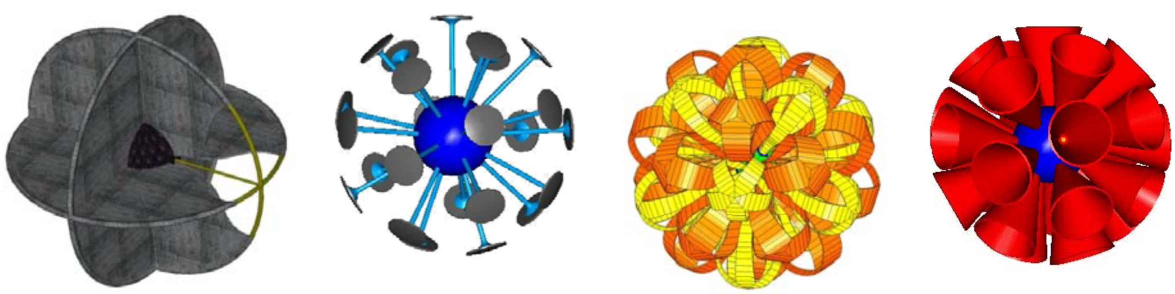


Figure 2. **NASA LaRC Deployable Open-Structure Tumbleweed Concepts, from left to right: Box-Kite, Dandelion, Eggbeater Dandelion, and Tumble-Cup**

IV. Mission Scenario

A mission scenario to explore gullies could be accomplished by first deploying a group of Tumbleweed rovers on the upslope plateau behind a crater or canyon with known gullies. Blown by the wind, the Tumbleweeds would first characterize the plateau, obtaining elevation data to determine the horizontal extent of it. Subsurface sounding of the plateau would be conducted to search for an aquifer and the overburden composition would be examined to estimate its thermal conductivity. After completion of the plateau investigation, two proposed options exist for directing the Tumbleweeds toward the gullies. For a completely passive Tumbleweed vehicle, a region would be selected with winds that generally blow across the upslope plateau in the direction of the gullies. However, in regions where the winds are uncertain, if a Tumbleweed could be equipped with the simple ability to stop and start (e.g., changing shape of the structure, deploying an anchor, etc.), a Tumbleweed could be made to stop on the plateau and wait for a favorable wind direction toward the gullies.

Moving down the slope, the next goal of the Tumbleweeds would be to search for evidence of a shallow aquifer, which would take the form of an ice plug beneath the overlying plateau, but close to the cliff face surface. As the Tumbleweed rolls down the slope, evidence of liquid water would be searched for on the exposed portions of the rock layers (i.e., a test for chemical signatures). A subset of the Tumbleweeds could also be deployed so as to avoid the gullies and roll down external slopes to gather data on the surrounding soils for comparative data. As the Tumbleweeds proceed down the gully channels, the interior would be examined to provide improved measurements regarding channel bed shape, depth, path (i.e., deflection around obstacles), etc. These measurements will present several challenges for the Tumbleweed vehicle, as some instruments will require a stationary period to allow proper integration time. One method would be to employ a deployable instrument package that could be dropped from the Tumbleweed as it rolls down the gully. The second method involves the stop/start capability mentioned previously. A Tumbleweed with this ability could halt at several locations within the channel to take data.

The Tumbleweeds would complete the mission by examining the debris apron to determine the size of particles being transported down-slope and the composition of the soil in the debris apron. At this point, depending on the condition of the vehicles, the mission could be extended by allowing the Tumbleweeds to continue taking measurements as they are blown about by the winds within the canyon or valley below.

V. Instrumentation

Science objectives to measure climate and to ascertain the existence of life require measurements of wind speed, wind direction, pressure, temperature, atmospheric gases and measurements for determining the existence of water and complex organic minerals. A critical sensor design objective is to make sensor weight negligible and to provide a high concentration of engineering and science measurements. Whenever possible, the components of the system should be integrated with structure of rover. A goal of this paper is not to demonstrate a complete suite of instruments but to demonstrate how key measurements can be acquired using the measurement system presented in this paper. Following a discussion of conventional sensors that are being studied for application to the Tumbleweed vehicle will be a discussion of a novel suite of sensors that use magnetic field responses as a means of acquiring measurements. This section describes magnetic field response sensors for detecting CO_2, O_2, NH_3 and H_2; ambient wind; presence of subsurface water and subsurface metals.

A. Conventional Sensors

The desired measurements outlined in Section II and summarized in the Tumbleweed mission scenario of Section IV could be accomplished using an instrument package of conventional sensors attached to the Tumbleweed. For example, ground-penetrating radar could be used to search for the existence of a subsurface aquifer beneath the plateau and an altimeter used to determine the horizontal extent of the plateau. As the Tumbleweed enters the slope and passes into the alcove region, a mini gas chromatograph/mass spectrometer (GC/MS) would be used to test chemical signatures in the atmosphere while an instrument such as an x-ray diffraction/x-ray fluorescence (XRD/XRF) would examine the chemical signatures on the exposed portions of the rock layers. As mentioned previously, these measurements present challenges because the Tumbleweed would need to stop for a period of time on the slope to allow adequate integration time for the instruments. In the interior of the channels, an imager would be needed to gather high-resolution data on the channel bed shapes, channel depths, etc. as the Tumbleweed rolls through the channel. This too would present challenges in determining how to integrate, point, and operate the cameras on a rolling platform. The GC/MS and XRD/XRF would be used once again to determine the composition of the surrounding gases and the soil in the debris apron as well as for the extended mission within the valley or canyon.

Another alternative would employ conventional sensors in a deployable package instead of attached to the Tumbleweed vehicle. This self-contained sensor package (or packages) could be dropped from a Tumbleweed as it rolls down a gully, taking measurements and relaying data back to Earth either through a central communications relay station (perhaps a Tumbleweed vehicle) or through an orbiting satellite.

B. Magnetic Field Response Sensors

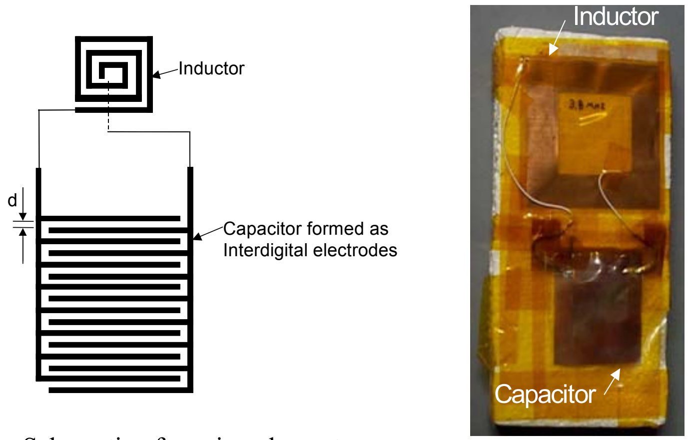
A recently developed measurement acquisition method has promise for providing the Tumbleweed rover with numerous sensors with a negligible aggregate mass[10-12] and may be able to take measurements while moving. A detailed discussion of the acquisition method can be found in Ref. 10. Key to the method is the use of magnetic field response sensors. A magnetic field response sensor is designed as a passive inductor-capacitor circuit that produces a magnetic field response whose attributes correspond to the value of the physical property that the sensor measures. The sensor acquires power via Faraday induction. The harmonic magnetic field response of the inductor serves as a means of transmitting the resonance. Key attributes of the magnetic field response are amplitude, frequency and bandwidth. Sensors are designed such that one of the attributes varies correspondingly with the measured physical state. A radio frequency antenna can produce the time varying magnetic field used for the Faraday induction as well as recieve the magnetic fields of the sensors. The use of magnetic fields for powering the sensors and for acquiring the measurements from the sensors eliminates the need for physical connection from sensing element to power source and data acquisition equipment. The architecture also eliminates the need to have a data acquisition channel dedicated to each sensor. Because the functionality of the sensors is based upon magnetic fields, they have potential use at cryogenic temperatures, extremely high temperatures, harsh chemical environments and radiative environments. Furthermore, the method allows acquiring measurements that were previously unattainable or logistically difficult because there was no practical means of getting power and data acquisition electrical connections to a sensor.

The magnetic field response acquisition method can be used to acquire measurements even when the sensor is embedded in material that is transmissive to the radio frequency energy that interrogates the sensing element. An advantage of this method is that the components for the acquisition system can be non-obtrusively added to the vehicle for which it is being used. An antenna can be produced as a metallic foil or as metal deposited on a thin dielectric film. Either version of the antenna can be mounted to an existing bulkhead or other structural components. For some applications, sensors can be fabricated using metal deposition methods. Metal deposition can be used to add sensors to a vehicle during manufacturing. Other advantages of the acquisition method are[19]:

- Physical connection to a power source (i.e., lead wires) is not needed
- Physical connection to data acquisition equipment is not needed
- Multiple sensing elements can be interrogated using the single data acquisition channel (used for antenna).
- Key components can be developed as metallic foils or thin films (inductors, antennae, some capacitor types)
- No line-of-sight is required between antenna and L-C(p) sensing element.
- The entire L-C(p) sensing element can be embedded in non-conductive material. For conducting material, the capacitive element can be embedded and the inductive element can be placed away from the surface of the conductive material.
- No specific orientation of sensing element with respect the antenna used to excite the sensing element is required except that they cannot be 90 deg to each other.
- Easy to implement into existing vehicles/plants
- Easy to add new measurements. No wiring is required. All that is required is a partition of a RF bandwidth used in the measurement spectrum and frequency/measurement correlation table.

In addition to the aforementioned attributes of the measurement system, key components of the system (sensors, antennae) could be deposited onto the rover instead of developing a separate structural support for the component and then securing it to the rover. The antennae used can be directly deposited on the inner surface of the rover as thin metallic films. Sensors can also be developed as thin films. Following this introduction will be a brief overview of the aquisition method. Following the overview will be a discussion of three sensor concepts for detection of chemical species; detection of surface/subsurface (less than 5 mm) water and metals; and to measure of surface wind vectors. The last section will discuss how the measurement system can be integrated into a planetary rover.

As discussed previously, a critical sensor design objective is to make sensor weight negligible, integrating the components of the system with the structure of the rover wherever possible, and to provide a high concentration of engineering and science measurements. Figure 3 shows a magnetic field response sensor. The inductor (L) is formed as a square spiral trace of copper. Interdigital electrodes have been used for the capacitor (C). The inductor and the capacitor have been deposited on a thin dielectric film. This section will describe methods in which the L-C circuit shown in figure 3 can be designed to perform many of the mission science measurements. The goal of the paper is not to demonstrate a complete suite of instruments but to demonstrate how key measurements can be acquired using the measurement system presented in this paper. This section describes magnetic field response sensors for detecting CO_2, O_2, NH_3 and H_2; ambient wind; presence of subsurface water and subsurface metals. Ref. 10 can be used as a guide for developing other science and engineering sensors.



a. Schematic of sensing element

b. Fabricated sensing element

Figure 3. **A magnetic field response sensor fabricated onto dielectric film. The inductor (L) is formed as a spiral of copper. Inter-digital electrodes have been use for the capacitor (C).**

Ambient Gas Sensors

Figure 4 depicts an array of four L-C circuits. Each circuit is a square spiral inductor electrically connected to an interdigital electrode within its perimeter. All four circuits are designed so that their range of resonant frequencies prior to and after exposure to their respective gases do not overlap. The method to detect a particular gas is to deposit a thin film of a chemical upon the surface of the capacitor that will react to the gas to form another chemical.[20] The dielectric can be a gas-responsive polymer or ceramic. The deposited dielectric serves as a chemical reactant. The gas serves as the other chemical reactant. Prior to exposure, the sensor has a baseline resonant frequency, ω_1. When the sensor is exposed to the gas, a chemical reaction produces a new chemical resulting in a new dielectric and thus a new resonant frequency, ω_2.

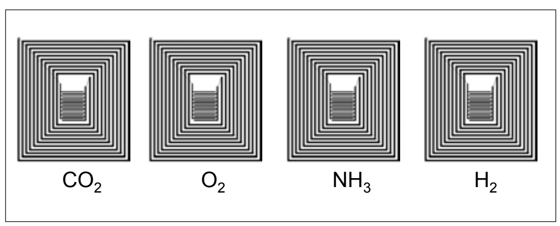


Figure 4. **Array of sensors for detection of atmospheric gases**

Chemical equation one summarizes the method of detection

$$\text{Reactant 1} + \text{Reactant 2} \rightarrow \text{Product}$$

$$\text{Dielectric 1} + \text{Gas} \rightarrow \text{Dielectric 2}$$

$$\omega_1 \rightarrow \omega_2 \qquad (1)$$

For example, a sensor for detecting ammonia, NH_3, in the atmosphere would have a dielectric coating of ammonium hydrogen sulfate, $\mathbf{N}H_4(HSO_4)$. Exposure of the ammonium hydrogen sulfate to ammonia would produce ammonium sulfate (Eq (2)) and thus a dielectric change.[20]

$$NH_3 + \mathbf{N}H_4(HSO_4) \rightarrow (\mathbf{N}H_4)_2SO_4$$

$$\text{Gas} + \text{Dielectric 1} \rightarrow \text{Dielectric 2} \quad (2)$$

Another dielectric coating for ammonia detection is a thin film of titanium nitride.[21] Titanium nitride is thermodynamically stable in air up to 500°C and is chemically stable in corrosive mediums.[21] The gases CO_2, O_2 and H_2 could be detected using thin film coatings of heteropolysiloxane, silicon nitride and palladium, respectively. Ref. 19 discusses the use of nano-tubed based gas sensors for monitoring CO_2, O_2 and NH_3.

Detection of Surface/Subsurface Water and Metals

This section presents a method for determining the presence of surface/subsurface water, metals or graphite. A magnetic field in proximity to a conductive material is attenuated. The distance within the material that the field can penetrate before being attenuated is called the skin depth, δ. This depth decreases if either the conductivity of the material, relative permeability or magnetic wave frequency increases.[22] When an active inductor that produces a time varying magnetic field is placed in proximity to a conductive surface, its magnetic field (and energy) is reduced inversely proportional to its distance from the conductive material. The rate that magnetic energy is attenuated is given by the following expression:[22]

$$H = H_0 e^{-\frac{z}{\delta}} \cos(\omega t - \frac{z}{\delta} - \frac{\pi}{4}) \quad (3)$$

The variables, H, H_0, z, δ and ω in Eq (3) are magnetic field intensity, initial magnetic field intensity, depth into the material, skin depth and frequency of the field. Skin depths for seawater and graphite are 200 mm and 1.59 at 1 MHz. Aluminum, chromium, copper, gold and silver have skin depths of 0.085, 0.081, 0.066, 0.075 and 0.064, respectively.[22] The skin depths for the metals are the same order of magnitude (O^{-1}). Seawater and graphite have skin depths of magnitude of O^0 and O^2. The inductance of the sensor is proportional to its induced magnetic field. The field decreases as the inductor distance to the conductive surface decreases. Therefore, the inductance also decreases as the inductor gets closer to the conductive material. As inductance decreases, the sensor resonant frequency increases. The response amplitude also decreases as the inductor gets closer to the conductive surface due to more energy being lost to the conductive material. The attenuation rate is proportional to the material skin depth. Using the measurement system described in this paper, water, metals and graphite could be discerned from each other by the changes in the sensor response amplitude with respect to changes in the response frequency as the sensor approaches a conductive material. This change is illustrated in figure 5. The amplitude decay with respect to increased frequency is much higher for materials with larger skin depths. Therefore, the slope, $\frac{dA}{d\omega}$, can be used as a means of discerning water, graphite and metals from each other.

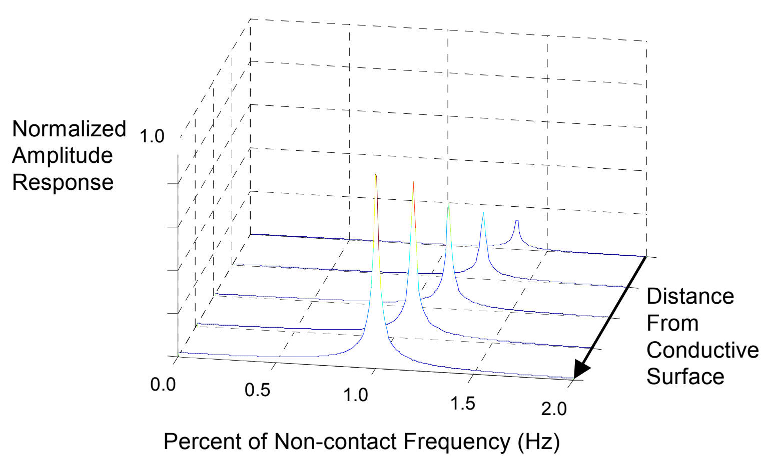


Figure 5. **Inductor magnetic field response to proximity to conductive surface**

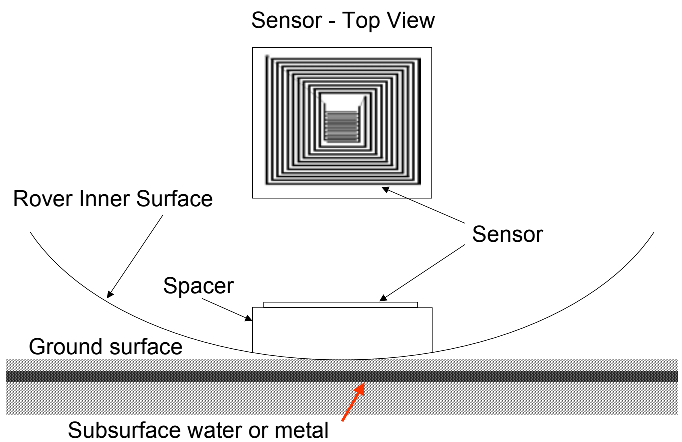


Figure 6 illustrates a sensor for determining the aforementioned slope. The sensor is mounted on a spacer (i.e., to provide a fixed separation between the sensor and the ground. Two points are used to measure the slope. The first point is the sensor response and amplitude when not in proximity to the ground (i.e., its baseline response). The second point is the measurement taken when the sensor is directly above the ground. Base upon the slopes, the on-board processor can determine if the measurement was due to water, graphite or metal.

Figure 6. **Sensor for detecting surface/subsurface water and metals.**

Wind Speed and Direction

A dynamic pressure sensor is produced by depositing an interdigital electrode and a square spiral inductor, figure 7, on a very elastic membrane (membrane 1). A thin-film deposition technique can be used for depositing the circuit. The membrane 1 is chosen so that it is stressed when exposed to a dynamic pressure. A second membrane (membrane 2) is used to reinforce the inductor. Membrane 2 is a hollow rectangle designed to cover the inductor but not the capacitor. Membrane 2 is used to keep any area change to the inductor negligible when exposed to dynamics pressure. When a surface wind blows against the sensor, it will cause the capacitor to deform. The distance between neighboring electrodes will increase thus changing the circuits resonant frequency. The wind speed is proportional to the change in resonant frequency.

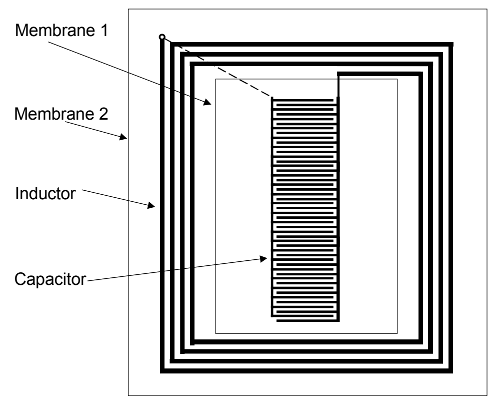


Figure 7. **Dynamic pressure sensor**

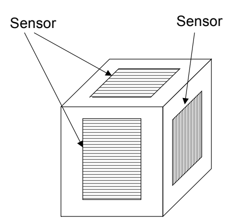


Figure 8. **Wind cube with dynamic pressure sensors on all exposed faces**

A cube, figure 8, is faced with the dynamic pressure sensors on each face. A stiff lightweight frame is used to support the cube. The inductance for each sensor is designed so that the range of resonant frequencies for each sensor does not overlap other sensors on the rover. Any wind can be reduced to components on any three faces of the cube. Therefore, a relative wind vector can be developed.

Implementation of the Measurement System and Sensors on a Tumbleweed Rover

This section discusses how the measurement system and sensors can be implemented on the Mars Tumbleweed Rover. The Boxkite concept, figure 2, will be used for this discussion. The components of the interrogation system are the control unit for regulating the antennae and the antennae. The control unit is mounted on the inner surface between the sails as shown in figure 9. Antennae are placed inside four of the eight sails. The antennae are deposited directly on a thin film. An additional four antenna can be placed on the other sails for redundancy. The antennae are located and oriented such that they are skewed to the axes of the sails. The goal of the antennae placement is to have each sensor within the magnetic field of at least one antenna. The wind cubes and gas sensor arrays are placed on one or more inner faces of the sails. On the inners surface, figure 10, of the curved portion of each sail are placed the water/metal detection sensors. The interrogation system will allow as many water/metal detection sensors as possible to be placed on the rolling surface of each hoop. Other engineering measurements can be incorporated into the rover without adding any additional wiring.[10]

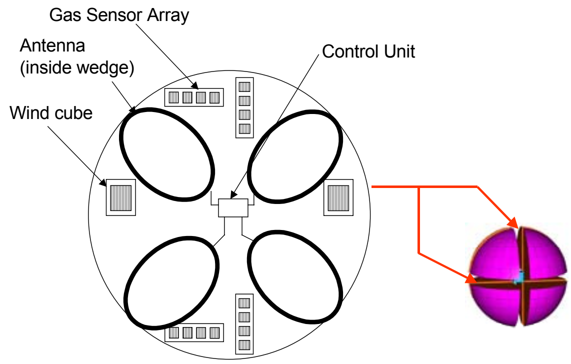


Figure 9. **Tumbleweed inner facet illustrating sensor and antennae positions**

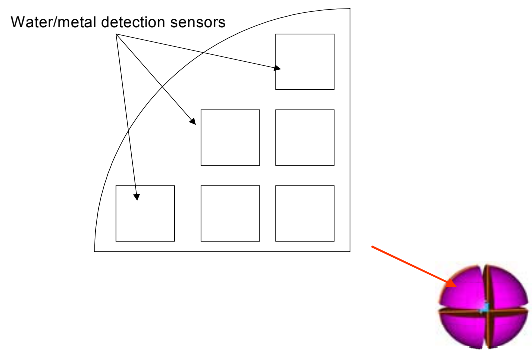


Figure 10. **Array of water/metal detection sensor placed on inner surface of each sail.**

VI. Conclusions

Gully formations have been discovered on the surface of Mars, the most likely candidate of their formation is liquid water; however, the source of this water is currently open to debate (i.e., liquid water aquifers (shallow and deep), melting ground ice, and snow melt). In-situ measurements are needed in four areas of interest: upslope plateau, alcove, channel, and debris apron in order to gain insight into the formation of gullies; however, they are currently inaccessible by conventional landers and rovers. A unique new vehicle known as the Tumbleweed rover could provide the capability to conduct preliminary investigations of the gullies. A set of conventional scientific instrumentation is defined for the Tumbleweed rover payload, including ground penetrating radar, mini-GC/MS, XRD/XRF, and imagers. An alternative extremely lightweight measurement acquisition method and sensor for planetary rovers is also presented that can be used to greatly increase the number of measurements performed while alleviating the science instrumentation mass requirements. Prospective uses of the measurement system and magnetic field response sensors used therein are illustrated to define how key measurements could be facilitated. Three magnetic field response sensors were presented for measuring wind speed, wind direction, key ambient gases and detection of surface/subsurface water. Many of the sensors can be directly deposited on the rover using deposition methods for thin-films resulting in sensors of negligible weight. The physics and/or chemistry of all the sensors were described. The gas sensor uses chemical reactions to create dielectric changes to their interdigital electrodes. Each gas sensor has a dielectric that would selectively react only with a desired gas. Variations of a magnetic field in proximity to a conductive surface would be used to ascertain to presence of surface/surface water or metals. Dynamic wind pressure would be determined using changes in interdigital electrodes spacing. Implementation of the method on the Mars Tumbleweed rover was also presented.

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